



Rotor blade online monitoring and fault diagnosis technology research

Tesauro, Angelo; Pavese, Christian; Branner, Kim

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Tesauro, A., Pavese, C., & Branner, K. (2014). *Rotor blade online monitoring and fault diagnosis technology research*. DTU Wind Energy. DTU Wind Energy E No. 0042

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Rotor blade online monitoring and fault diagnosis technology research



Department of Wind Energy E Report 2014

Angelo Tesauro, Christian Pavese, Kim Branner

DTU Wind Energy E-0042

ISBN: 978-87-92896-72-8

May 2014

DTU Wind Energy
Department of Wind Energy



Authors: Angelo Tesauro, Christian Pavese, Kim Branner

Title: Rotor blade online monitoring and fault diagnosis technology research

Department: Department of Wind Energy

Summary (max 2000 characters):

Rotor blade online monitoring and fault diagnosis technology is an important way to find blade failure mechanisms and thereby improve the blade design. Condition monitoring of rotor blades is necessary in order to ensure the safe operation of the wind turbine, make the maintenance more economical, and accumulate data for evaluation of the blade design.

In this report the implementation of condition monitoring methods is described focusing on the kind of sensors that have to be mounted on the blades in order to detect different changes to the blades. These changes are damage progression, unbalancing of the rotor, icing and lightning. Research is done throughout the world in order to develop and improve such measurement systems. Commercial hardware and software available for the described purpose is presented in the report.

ISBN: 978-87-92896-72-8

May 2014

Contract no.:

104.Kina.1.MFS.4-1-2-5

Project no.:

43186

Sponsorship:

Sino-Danish Renewable Energy
Development (RED) Programme

Front page:

Pages: 48

Tables: 3

References: 48

Technical University of Denmark

Department of Wind Energy
Frederiksborgvej 399
Building 118
4000 Roskilde
Denmark
Phone 46775470

kibr@dtu.dk
www.vindenergi.dtu.dk

Preface

This report is deliverable 3.1 and 3.3 of the project “Wind turbine rotor blade testing technology research and platform construction”. The project is supported by the Renewable Energy Development (RED) programme in which the Chinese and Danish governments are cooperating and aiming at institutional capacity building and technology innovation for renewable energy development.

This particular project is a partnership between the Chinese Baoding Diangu Renewable Energy Testing and Research Co., Ltd., a national wind and solar energy key laboratory for simulation and certification and from Denmark the Department of Wind Energy, Technical University of Denmark, a Danish wind energy research department that has provided a major part of the wind energy research in Denmark and is one of the leading wind energy research institutions in the world.

The project will focus on research for on-site, full-scale and down-scale structural testing of wind turbine rotor blades. An advanced blade on-site monitoring platform and full-scale testing platform will be constructed to strengthen the capacity of wind turbine blade testing and demonstrated in Baoding, city of Hebei Province in China.

The project will provide the manufacturers with the possibility to do comprehensive blade testing in order to achieve test data for fulfilling requirements of standards and in order to obtain better and more optimized blade design. Meanwhile advanced experiment tool and valid test data can also be provided for the research and certification institutions in order to develop better design methods and certification guidelines and standards.

The project has three main parts. The first part is research in full-scale and down-scale structural testing of wind turbine blades as well as condition monitoring for on-site testing of whole wind turbines. The next part is construction of platforms in China for full-scale fatigue testing of blades and on-site condition monitoring of wind turbines. Finally, the last part is to demonstrate the full-scale fatigue testing and the on-site condition monitoring.

Roskilde, Denmark, May 2014

Content

| | |
|--|----|
| Summary | 6 |
| 1. Introduction | 7 |
| 2. Crack detection systems | 8 |
| 2.1 Introduction | 8 |
| 2.2 Working principles and description of the detection methods | 8 |
| 3. Icing | 15 |
| 3.1 Icing definition | 15 |
| 3.2 Icing classification | 15 |
| 3.3 Consequences on wind turbines | 16 |
| 3.4 Icing events classification | 16 |
| 3.5 Icing detection methods based on a anemometers | 17 |
| 3.6 High frequency vibrating probe systems | 18 |
| 3.7 Icing detection methods based on power curve analysis | 19 |
| 3.8 Icing detection methods based on change in natural frequencies of the blades | 20 |
| 3.9 Other methods | 21 |
| 3.10 Commercial products for icing detection | 23 |
| 3.11 Conclusion | 23 |
| 4. Rotor unbalance | 25 |
| 4.1 Working principles | 26 |
| 4.2 Practical configuration | 27 |
| 4.3 Commercial systems | 28 |
| 5. Lightning detection systems | 29 |
| 5.1 Introduction | 29 |
| 5.2 Working principles | 29 |
| 5.3 Survey of available equipment | 33 |
| References | 43 |
| Acknowledgements | 47 |

Summary

Rotor blade online monitoring and fault diagnosis technology is an important way to find blade failure mechanisms and thereby improve the blade design. Condition monitoring of rotor blades is necessary in order to ensure the safe operation of the wind turbine, make the maintenance more economical, and accumulate data for evaluation of the blade design.

In this report the implementation of condition monitoring methods is described focusing on the kind of sensors that have to be mounted on the blades in order to detect different changes to the blades. These changes are damage progression, unbalancing of the rotor, icing and lightning. Research is done throughout the world in order to develop and improve such measurement systems. Commercial hardware and software available for the described purpose is presented in the report.

1. Introduction

This report is a deliverable under activity 3. The objective of this activity is: The objective is to provide state-of-the-art information about condition monitoring and fault diagnosis technology on wind turbine blades. Furthermore the objective is to study blade failure types, failure mechanism and their cause.

An investigation of public available information about solutions adopted in Denmark and worldwide for condition monitoring of wind turbine blades is carried out. Both out-of-the shelf and innovative products are considered. Each method is presented, explaining the working principle along with installation procedures. Advantages and drawbacks are analyzed. Promising techniques are highlighted and new ideas are investigated, from a conceptual point of view.

The implementation of condition monitoring methods is focusing on the kind of sensors that have to be mounted on the blades in order to detect different changes to the blades. These changes are damage progression, unbalancing of the rotor, icing and lightning. Research is done in order to find most suitable locations for each kind of measurement system. Commercial hardware and software available for the described purpose are also presented in the report.

2. Crack detection systems

2.1 Introduction

As wind turbines size increases, and with that the initial capital investment, there is an increasing need to monitor the health of these structures. A fundamental action for the operators is the acquisition of early indications of structural or mechanical problems. This allows to better plan for maintenance, possibly operating the machine in a de-rated condition rather than then taking the turbine off-line or, in case of an emergency, shutting the machine down to avoid further damage.

The most expensive components of a wind turbine are the blades, which account for 15-20% of the initial capital investment. It is therefore important to set up a system able to constantly monitor the health of these components, in order to avoid a critical failure that could force the operator to substitute the blade. Moreover, a damaged blade in operation can affect not only the power production, which decreases because of losses on the aerodynamic properties of the blade, but also the safety of the surrounding areas, in case pieces are thrown from the rotating blade. Moreover the health of the entire wind turbine structure can be affected, as the performances are very sensitive to the blade shape. In the worst case scenario, small damages can evolve, if not monitored and lead to blade failure.



Figure 1: Wind turbine blade crack.

2.2 Working principles and description of the detection methods

As already mentioned, structural damages on wind turbine blades can induce catastrophic failure of the entire machine. A reliable structural health monitoring (SHM) system can detect

structural damages on the blade within a certain range of accuracy, early enough to prevent dangerous consequences that can affect the cost of the investments or the safety of the surrounding areas. If reliable information is gathered through such a system, the operator can improve safety considerations, minimize down time, lower the frequency of sudden breakdowns, associate huge maintenance and logistic costs and provide reliable power generation [1]. Damages on a blade can occur in various ways and they can involve different structural parts of the component (Figure 2).

A list of typical structural damages that can be observed on a wind turbine blade is reported in Table 1 [2] [3] [4] [5].

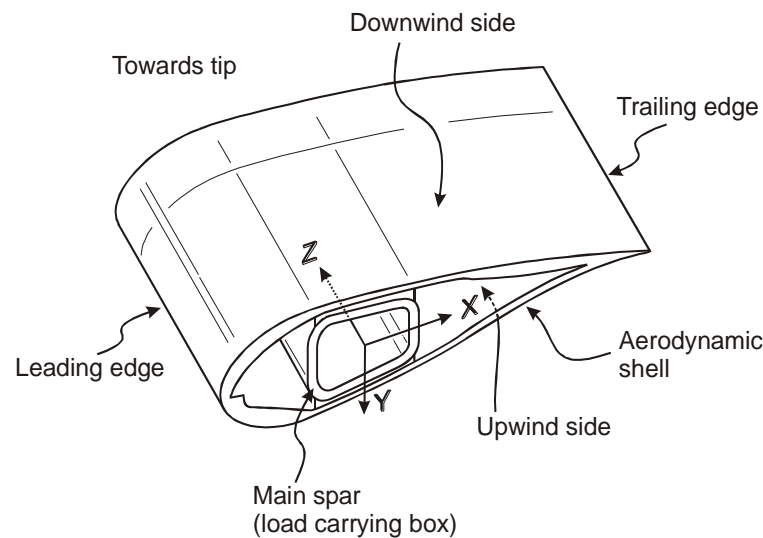


Figure 2: Main parts of a wind turbine blade section [2].

| Type | Description |
|---------------|---|
| Type 1 | Damage formation and growth in the adhesive layer joining skin and main spar flanges (skin/adhesive debonding and/or main spar/adhesive layer debonding) |
| Type 2 | Damage formation and growth in the adhesive layer used to join the skins along leading and/or trailing edges (adhesive joint failure between skins) |
| Type 3 | Damage formation and growth at the interface between face and core in sandwich panels in skins and main spar web (sandwich panel face/core debonding) |
| Type 4 | Internal damage formation and growth in laminates in skin and/or main spar flanges under tensile or compression load (delamination driven by a tensional or a buckling load) |
| Type 5 | Splitting and fracture of separated fibres in laminates of the skin and main spar (fibre failure in tension; laminate failure in compression) |
| Type 6 | Buckling of the skin due to damage formation and growth in the bond between skin and main spar under compressive load (skin/adhesive debonding induced by buckling, a specific type 1 case) |
| Type 7 | Formation and growth of cracks in the gel-coat; debonding of the gel-coat from the skin (gel-coat cracking and gel-coat/skin debonding) |

Table 1: Typical damage of wind turbine blades [2] [3] [4] [5].

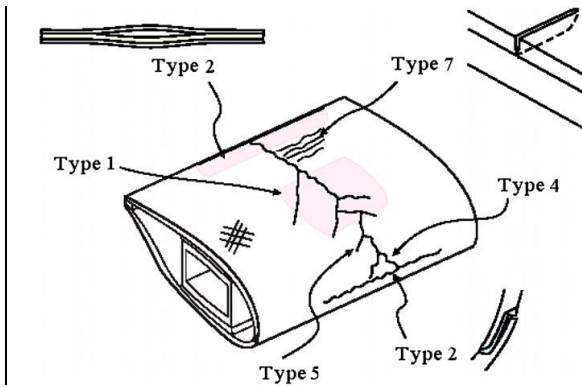


Figure 3: Wind Turbine Blade common damages types [2].

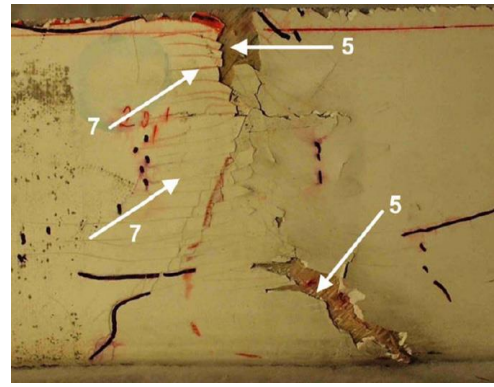


Figure 4 - Damage type 5 (laminate failure in compression) and type 7 (gel coat cracking) at the bottom of the leading edge [2].

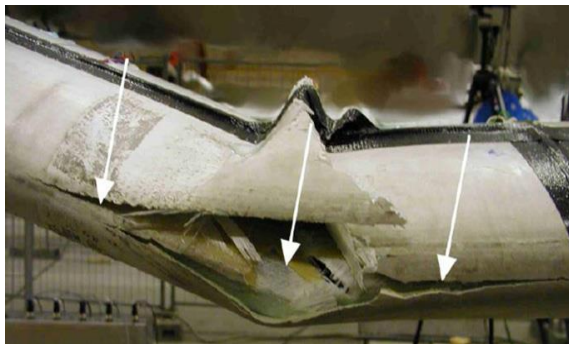


Figure 5: Damage type 2 (adhesive joint failure between skins) at the leading edge [2].

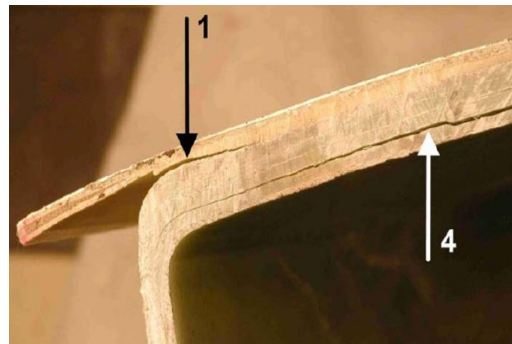


Figure 6: Damage type 1 (main spar flange/adhesive layer debonding) and type 4 (delamination by buckling load) [2].

A blade crack detection system is composed by two main parts: a built-in network of sensors for collecting response measurements, and a data analysis algorithm/software for interpretation of the measurements in terms of physical condition of the structure [6]. A series of technologies able to detect structural damages on wind turbine blades are reported in the next paragraphs.

It is important to remark that there are no companies on the market providing a full package of software and hardware for detection of structural damages on wind turbine blades. The development of these technologies as commercial products is still in the early stages. It is therefore not possible to report a detailed comparison between availability and costs of the technologies used to implement different methods for crack detection.

Another issue is that none of the technologies reported in this chapter or used by the academia to perform research in this field can be used to predict where structural damage appears and develops on a blade under certain loading condition. It is therefore extremely complicated to find a useful application for these methods on wind turbines in operation; in fact, there is no public information on SHM of crack detection on blades mounted on operating wind turbines.

All the information gathered in this section is based on one side, on a literature review of the technologies available in this field, and on the other, on information retrieved from collaborations between DTU Wind Energy, companies and other universities.

2.2.1 MA-based approach (Modal Analysis)

The methods based on Modal Analysis (MA) are among the earliest and most common damage detection approaches used, principally because they are simple to implement on structures of any size. The concept behind these methods is straight forward: the dynamic response of a structure, excited through external shakers or different sorts of actuators, is monitored using sensors such as accelerometers or strain gauges [7] [8]. The idea behind this technology is to detect frequencies and mode shapes of the structure under a certain excitation. Since the modal parameters are strictly connected to the physical properties of the structure, changes such as reduction of stiffness resulting from the onset of cracks or loosening of a connection cause detectable changes in the modal properties [9] [10] [11] [12]. Structural damage detection is based on a comparison between the response from a baseline signal, which is taken when the structure is still intact, and the response from a signal detected when the structure is damaged [13] [14].

The most used configuration for this approach requires a number of accelerometers installed along the structure. Other configurations are discussed in literature, but they are only variations on the basic concept of installing arrays of sensors along the blade to detect modal properties. These sensors can be different for type and working principle, but the most used, accurate, reliable and relatively convenient are the accelerometers.

DTU Wind Energy is recently collaborating with Brüel & Kjær in a project related to the detection of structural damages on wind turbine blades. The system used by the company consists of approximately 20 tri-axial piezoelectric accelerometers installed on the leading and the trailing edge of a 34 m SSP Blade. The signals from the sensors are acquired and processed using B&K in-house software. This configuration is being tested to detect crack of various length on the adhesive joint of the blade trailing edge. The excitation system consists of external manual and automatic actuators.

Regarding the excitation method, one of the interesting procedures tested in this project is related to the application of Operational Modal Analysis:

“Operational Modal Analysis is based on measuring only the output of a structure and using the ambient and operating forces as unmeasured input. It is used instead of classical mobility-based modal analysis for accurate modal identification under actual operating conditions, and in situations where it is difficult or impossible to control an artificial excitation of the structure.

Many civil engineering and mechanical structures are difficult to excite artificially due to their physical size, shape or location. Also civil engineering structures are loaded by ambient forces, for example, waves (offshore structures), wind (buildings) or traffic (bridges), and operating machinery exhibits self-generated vibrations. These natural input forces, which cannot easily be controlled or correctly measured, are used as unmeasured input for Operational Modal Analysis. In classical modal analysis, they would be superimposed as noise on the controlled artificial forces and would provide erroneous results.

For mechanical structures like aircraft, vehicles and operating machinery there is a need to determine real-life modal parameters using actual operating conditions, that is to say, actual boundary conditions, actual spatial and frequency distributions of forces and actual force and response levels.” [15]

Brüel & Kjær is using this project to set up a new commercial product that can be used for crack detection on wind turbine blades. The development of this system is still in its early stage, but the company offers a wide selection of sensors (especially piezoelectric accelerometers) suitable to configure an approach able to detect structural damages [16] [17]. The software commercialized by B&K can be found in [18].

The accuracy and the cost of this system depend on the amount of sensors that have to be mounted on the structure. According to the dimension of the wind turbine blade, a certain amount of sensors must be mounted to detect the modal properties of the structure within a certain range of accuracy; the optimization of the number of accelerometers to install on the blade according to its dimensions is currently under investigation.

2.2.2 Guided Wave (GW) analysis approach

Guided Waves (GW) are defined as stress waves forced to follow a path defined by the material boundaries of the structure. For example, when a plate is excited at high frequency, the stress waves travel in the plate along its axes from the excitation source. The plate is “guiding” the waves within its confines. In GW SHM, an actuator generating GWs is excited by some high-frequency pulse signal. In general, when a GW is incident on a structural discontinuity (which needs to have a size comparable with the GW wave length), it scatters GWs in all directions. This structural discontinuity can be a structural damage due to cracks [19]. As for the MA-based approaches, this procedure is based on the comparison between a baseline signal obtained for the “healthy state”, and a signal recorded when the structure is damaged.

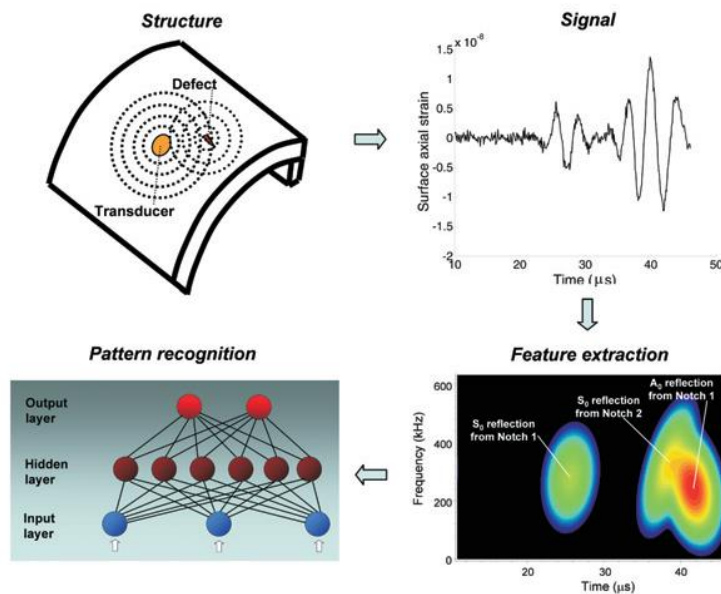


Figure 7: The four essential steps in GW SHM [19].

This method had been tested on a CX-100 wind turbine blade in two different experiments:

1. Detection of a simulated damage introduced by applying industrial putty [8]
2. Fatigue loading [13] [14]

In both cases, to detect GW propagation, a system based on piezoelectric active-sensors had been used (active sensors work as actuators and transducers).

Even if the tests had slightly different purposes, they showed essentially the same result: the sensors are unable to detect the structural damage, unless the crack is physically very close to the sensing equipment. In [8] this is attributed to the high damping present in composite structures, which limits the distance that the GW can travel. Conclusion: in this case, the propagation of GWs is strongly affected by the high complexity of the geometry and the layup of a wind turbine blade. A better study concerning the mathematical formulation behind the development of these phenomena in such complex structures is required.

Regarding the costs and the accuracy, the GW SHM transducers are generally expensive and several issues related to supporting electronics, robustness and packaging have been reported [19]. A next reliable application of this method on crack detection of wind turbine blades is very difficult.

2.2.3 Acoustic Emission (AE) events detection method

Processes such as cracking, deformation, debonding, delamination, impacts, crushing and others produce localized transient changes in stored elastic energy with broad spectral content. This changes travel as acoustic waves.

Acoustic Emission (AE) monitoring during loading of wind turbine blades can reveal audible cracking sounds that can identify a structurally damaged area [20] [21] [22]. Different types of sensors can be used to detect AE waves like piezoelectric or piezoceramic patches. This technology can be more accurate than the GW analysis approach, but in cases where high accuracy of damage evaluation is needed, the number of sensors must be increased and subsequently the number of data output of the signal processing system has to increase [5]. A large blade would need a huge amount of AE sensors, assuming that the location where the crack starts is not known a priori.

Moreover, a correct detection of a cracking sound coming from the formation of a structural damage can be performed only if the system is able to constantly retrieve data and post-process it: some damages produce cracking sounds when they are propagating; in case the propagation stops not producing any further typical sound, and the system is “sleeping” or not connected, the method is not be able to detect the presence of the damage. This is impractical and computationally expensive since the system is forced to handle a huge amount of data being constantly connected to avoid the risk of missing the formation of a crack.

2.2.4 Thermal Imaging (TI) method

Thermal imaging method is a subsurface defects or anomalies detection method owing to temperature differences observed on the investigated surface using sensors or cameras [5] [23]. This method uses the thermoelastic effect: the temperature change of elastic solid, due to the change of stress. Higher acoustical damping, higher stress concentration and different heat conduction near the defective region are expected, and hence the defective region will have a higher temperature.

In [24], a method involving the principle of thermoelastic effects has been used to monitor the stress distributions on a 13.4 m GPR blade under fatigue loading. The measurements were harvested using a thermoelastic stress camera (TSA) by CLRC (United Kingdom). These data allowed locating stress concentrations and “hot spots” on the blade: this information is useful to perform SHM, preventing the formation of damages in case the stress distributions exceed a certain threshold.

There is no information regarding the use of this method by the industry: the equipment to perform TI is highly expensive and the detection of temperature differences on a localized scale is difficult, because they are small and short-lived, due to the conduction into the rest of the specimen and convection into the surroundings [24].

3. Icing

“There is a large need for more and better icing measurements, especially at wind turbine blades. Today's instruments are not reliable and accurate enough. As long as such instruments don't exist, large uncertainties remain in the understanding of icing on wind turbines in general and in the development of new wind turbine ice accretion models.” (28. René Cattin)



Figure 8: Example of icing on a wind turbine blade.

3.1 Icing definition

Atmospheric icing is defined as the accretion of ice or snow on structures, which are exposed to the atmosphere.

3.2 Icing classification

1. **Rime Ice:** Super cooled liquid water droplets from clouds or fog are transported by the wind. When they hit a surface, they freeze immediately. Rime ice typically forms in the temperature range $[-20^{\circ}\text{C}, 0^{\circ}\text{C}]$. The most severe rime icing occurs at exposed ridges where moist air is lifted and wind speed is increased. Its formation is asymmetrical (often needles), usually on the **windward side** of a structure. Its crystalline structure is rather irregular, surface uneven, and its form resembles glazed frost.

Two types of Rime Ice are found:

- a. **soft rime** is formed when the droplets are small. Soft rime is a fragile, snow-like formation consisting mainly of thin ice needles or flakes of ice. The growth of soft rime starts usually at a small point and grows triangularly into the windward direction. It has a density in the range [200kg/m³, 600 kg/m³] and it can be more easily removed.
 - b. **hard rime** is formed instead when the droplets are bigger. It is opaque, usually white, ice formation, which adheres firmly on surfaces making it very difficult to remove. The density ranges between [600kg/m³, 900 kg/m³].
2. **Glaze**: At slightly higher temperatures, namely in the range [-6°C, 0°C] another kind of ice can occur. That is glaze, a smooth, transparent and homogenous ice layer, which adheres firmly to the structure surface. When the temperature approaches 0 degrees, the water droplets hitting the surface do not freeze completely. A layer of liquid water forms and, due to wind and gravity, may flow around the object and freeze **also on the leeward side**. Glaze presents a density of about 900 kg/m³.
3. **Wet snow**: at temperatures above zero, more specifically in the range [0°C, +3°C], partly melted snow crystals with high liquid water content become sticky and are able to adhere on the surface of an object. Wet snow has a density comprised between 300 and 600 kg/m³. The wet snow freezes if a drop in the temperature follows the snow accretion.
4. The last phenomenon related to icing of solid contours is called **sublimation**. In this case water vapour becomes directly ice on the surface of the object of interest, without passing through the liquid state. The product of this phase transition is called **hoarfrost**, which presents low density, adhesion and strength. Hoarfrost does not cause significant loads on structures. [25]

3.3 Consequences on wind turbines

Ice formation on wind turbine blades causes several problems:

- Excessive blade loading
- Ice throw
- Decrease of aerodynamic properties
- Decreased blade life due to additional loading
- Asymmetric drive train loading

It is therefore essential to monitor it.

3.4 Icing events classification

An icing event can be described with the following expressions, applicable to all structures and instruments exposed to atmospheric icing:

- **Meteorological icing**: Period during which the meteorological conditions for ice accretion are favourable (active ice formation)
- **Instrumental icing**: Period during which the ice remains at a structure and/or an instrument or a wind turbine is disturbed by ice.

- **Incubation time** is defined as the delay between the start of meteorological and the start of instrumental icing (dependent on the surface and the temperature of the structure).
- **Recovery time**: Delay between the end of meteorological and the end of instrumental icing (period during which the ice remains but is not actively formed)

The following sketch illustrates how icing affects a cup anemometer, for instance, according to the definitions described above.

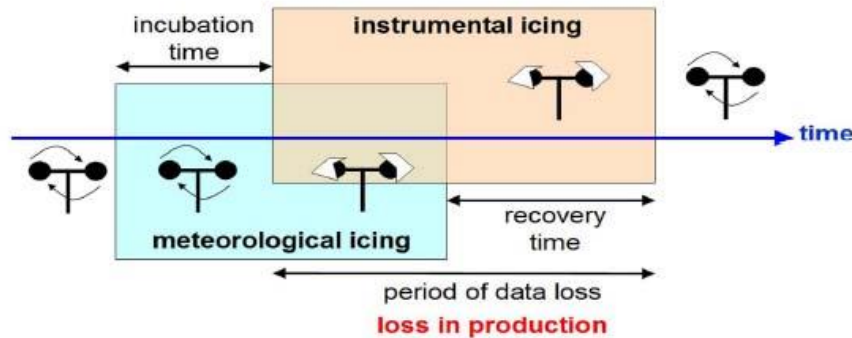


Figure 9: Icing events definition.

“When meteorological conditions for ice accretion are given (start of the meteorological icing), there is a certain delay – the incubation time - until ice accretion at the anemometer begins. As soon as there is ice on the sensor (start of the instrumental icing), the measurement is disturbed. Ice is accreted continuously on the sensor until the meteorological conditions for icing are not present anymore (end of the meteorological icing). But the ice will remain at the instrument for a certain time – the recovery time - until it melts or falls off (end of the instrumental icing). This delay can be much longer than the period of meteorological icing. Although the meteorological conditions for ice accretion are not present anymore, the readings of the instrument have to be discarded until the instrumental icing has ended.” [26]

3.5 Icing detection methods based on a anemometers

These methods are indirect methods, in the sense that they do not detect ice formation on the blades and that is their main drawback.

3.5.1 Working principle

The sensing instrument can be an anemometer, which, as described in the previous Chapter, stops spinning in correspondence of specific temperature ranges. This is used as a criterion to stop pre-emptively the turbine to avoid damages. This simple method for ice detection is very conservative and does not give any indication, neither on the loading on the blades, nor on the turbine. It should not be considered as a monitoring tool but rather an operational safety system.

This method can be improved by using two anemometers. The underlying idea is to compare the measurements from a heated instrument and an unheated one, in order to identify the icing conditions.

3.5.2 Reliability and drawbacks

“This has been proven to be a robust approach; however, it can deliver only information on instrumental icing. An ongoing study is adding a third anemometer, which is heated only in intervals during periods of meteorological icing. If successful, this approach might be able to deliver the needed information on meteorological icing, too”.

Another drawback comes from the anemometer location. Anemometers are typically located at the top of nacelle of wind turbine. Often the problem is that they are not able to measure the actual conditions of the rotor blades, as the physical conditions about a rotating blade and a sensing probe, stationary on the nacelle can be very different [27].

This is a common drawback for all the instruments placed on the nacelle or on a met-mast nearby.

3.5.3 Mounting precautions

“Attention must be paid also to the positioning of the anemometer and wind vane in icing conditions. To gain accuracy, the normal procedure consists in heating the sensor to avoid ice formation on it. In severe icing conditions the accuracy gained through heating is quickly lost, if neighbouring objects such as booms and masts are allowed to collect ice. Therefore surrounding objects need to be heated as well. Heating cables for mounting booms are needed for sites with severe icing.” [28]

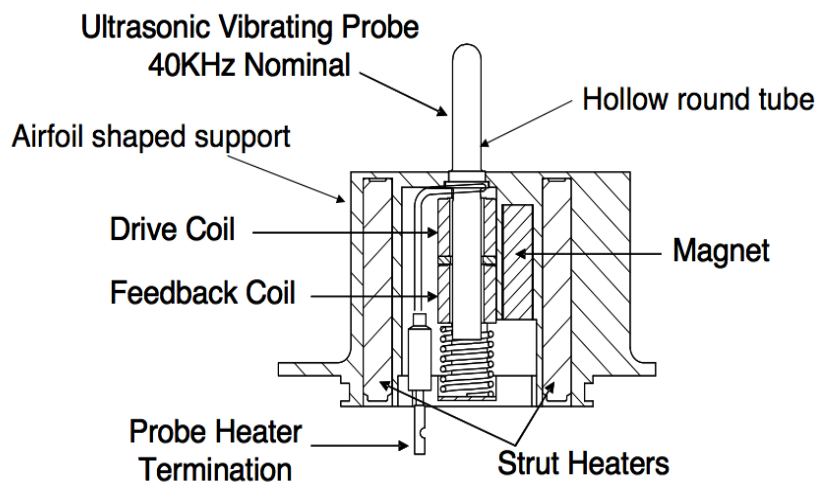


Figure 10: Vibrating probe system [5].

3.6 High frequency vibrating probe systems

3.6.1 Working principle

Another idea is to detect the accretion of ice on a small object, which experiences the same atmospheric conditions of the blades but is much more controllable. Such idea is implemented using a probe. Using a magnetostrictive technology is possible to “drive the sensing probe to resonate at its natural frequency. As ice accretes on the probe, a shift in resonance frequency

occurs. When the resonance frequency reaches the setpoint, an ice signal is activated. Upon user command, the heaters turn on for a predetermined time to remove the ice.” [5] [6]

On the bright side this is a well-proven technology used on aircrafts for many years.

3.6.2 Drawbacks and Mounting precautions

The following points can result in wrong measurements:

- Ice detectors are typically located at the top of nacelle of wind turbine. These ice detectors can be used to detect prevailing icing conditions and to predict the conditions of the rotor blades. But often the problem is that ice detectors are not able to measure the actual conditions of the rotor blades [27].
- Ice accretion is dependent upon a complex heat transfer which is a function of, among others, Geometry, airspeed, Liquid Water Content, temperature.
- Differences in geometry and local flow-fields can cause differences in the freezing fraction and Critical Temperature for a given surface, meaning that ice presence on the sensor, mounted on the nacelle does not necessarily means that ice is also present on the blades. Moreover, differences in Critical Temperature between the blades and the ice detector surface need to be evaluated, including installation effects.
- Droplet impingement is key to proper performance of ice detection system CFD analysis must be performed to ensure proper impingement.
- Locations with possible higher LWC or airspeed than free-stream conditions must be identified.

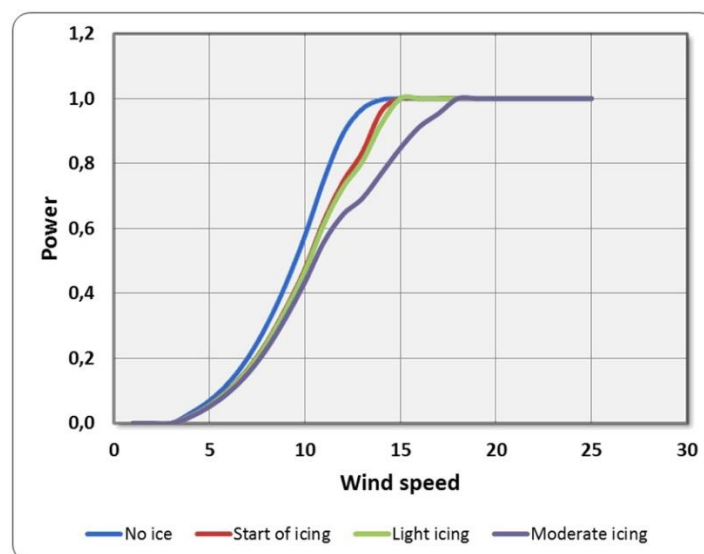


Figure 11: Power curve modification due to ice accretion on the blades [4].

3.7 Icing detection methods based on power curve analysis

3.7.1 Working principle

Ice accretion on rotor blades changes the surface roughness and the shape of the airfoil, thus affecting aerodynamic properties and aerodynamic balance of the rotor. From a comparison

between the actual power output of the turbine and the nominal for the same wind speed, it might be inferred ice presence on the blades.

3.7.2 Reliability and drawbacks

This approach has been proven to be very robust and efficient to detect iced blades during operation **under strong wind**. The disadvantages of this method are that ice cannot be detected during stand still of the rotor and the reduced power output can be result of other phenomenon than icing of rotor blades, for example yaw misalignment and wake of another turbine. The turbulence of wind is causing disturbances to power, which hinders the indication of reduced power output [26].

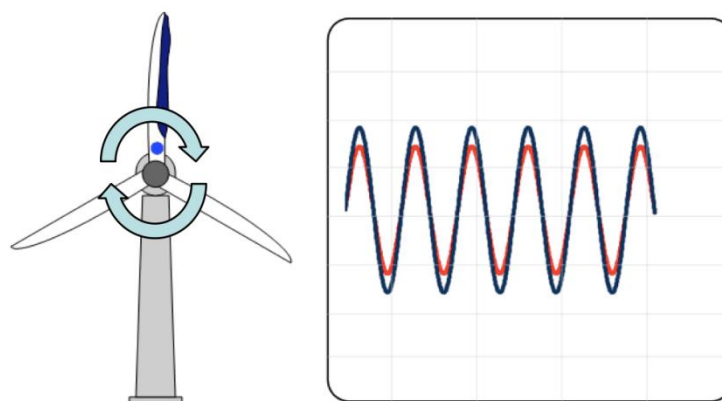


Figure 12: Bending moment in the root of the blade with and without ice.

3.8 Icing detection methods based on change in natural frequencies of the blades

An alternative approach consists in identify the ice on the blades through changes in their eigen-frequencies or mass. A weight increase can be due to icing or other causes like water absorption, debris or liquids leaking from the pitch bearing or hub into the blades. While the weight increase due to water absorption or oil leaking happens over longer time, in order of weeks, ice accretion can be seen as a fast weight increase. The time-lapse need for ice-formation is in the order of hours. This is a criterion to distinguish between long term water/debris absorption and ice formation.

3.8.1 Working principle

The method consists in measuring the weight of the blade by means of the bending moment in the root or alternatively the natural frequencies of it. When the turbine is running the root bending moment gives a sinusoidal signal proportional to the weight of the blade. When ice forms on the blade the amplitude of the bending moment increases. By analyzing the time series of the bending moment it is possible to distinguish ice formation.

When the rotor is stationary (wind speed below cut-in speed) the information about the ice formation can be retrieved performing a Frequency Domain Analysis of a resonant frequency. In fact, even a gentle breeze (>3 m/s) excites the blades that start vibrating according to their natural frequencies.

The natural frequencies change when there is ice on the blade. This can be seen as a shift in the resonances in the spectrum of the signal, as shown in the sketch below.

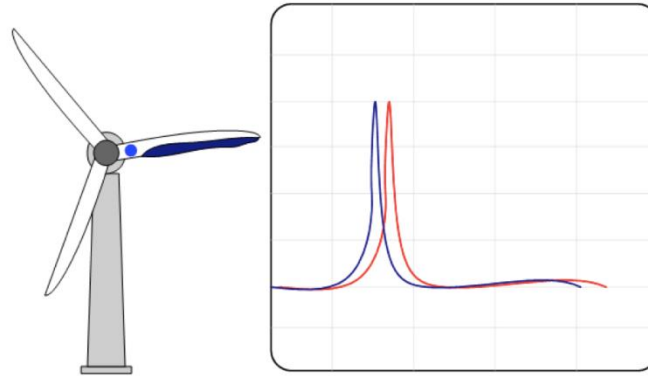


Figure 13: Natural frequency peak shifts because of the added mass.

3.8.2 Which sensors

Four strain gauges (rosettes) positioned in the root of the blade to detect two bending moments. Their average value can be representative of the weight of the blade. Using the properties of the laminates close to the root (which should be known), it is possible to retrieve the bending moments acting on the blade root. To avoid temperature-related problems and deterioration of performance due to fatigue (thermal drift or low reliability) optical strain gauges should be used.

Alternatively, accelerometers can be installed in the blades at some distance from the root (in order to make them more sensitive to the vibration modes, which would otherwise be very small in the root, being this encastered to the hub), instead of strain gauges.

3.8.3 Reliability

The manufacturers claim that these systems work reliably, however there exist hardly any independent test cases from R&D projects. Some of these systems depend on access to the current pitch data of the wind turbine, which might not be accessible depending on the manufacturer. Some of these systems are also able to measure the ice load. Here again, an independent study from an R&D project is not available [28].

3.9 Other methods

A variety of methods for ice detection is found in scientific literature. Most of them are not suited for the application on operating wind turbine blades. Other methods are at a research stage and the practical applicability has not been demonstrated yet or seems difficult. Here we list some of them.

3.9.1 Methods based on optical scanning of the blades

“A variety of icing sensing technologies has been introduced such as electromagnetic and electro-acoustic devices, resonant beam sensors, infrared absorption sensors, etc. to address this need. Most systems involve mechanical contact of some sort while a few are non-contact.”

For the purpose of this project only non-contact devices are considered, since a requirement is to install them on an operating turbine, which makes contact type devices impractical or impossible.

*“A number of optically based remote detection systems have been described in the literature. Most are based on absorptive and reflective properties of the ice and also its birefringence. For example Pernick (1999) describes a method that involves scanning a surface of an aircraft with **laser light of two wavelengths and using the absorptive characteristics of water [...] and ice** to determine the composition of an ice layer. Pernick mentions the possibility of using absorption to determine the thickness of layers, however the focus is mainly on detecting the presence of the materials and thickness measurement is not included in the patent claims. It also appears that Pernick's system would only work on clear ice, i.e. glaze ice, and would not be suitable for rime ice or frosted glaze ice.” [29]*

These last considerations make the method proposed by Pernik unsuited for the purpose of monitoring the blades of wind turbines, as the occurrence of rime-ice cannot be excluded a-priori.

*“A similar method, based on **absorption of infrared light**, is described by Sinnar (1989) and in this instance the **capability of measuring thickness** appears in the patent claims. We speculate that the effectiveness of the technique could be reduced by the effect of a frosty surface on the ice or inclusions (air bubbles) in the ice that influence the intensity of radiation detected by the sensor.”*

“The same considerations would apply to the Road Surface State Sensor DSC111 device briefly described by Bridge (2008). The technology appears to work on the same principles as that of Pernick (1999) and Sinnar (1989) and it is stated that the technology can detect and measure thicknesses of layers of water, ice or snow. Christian et al. (1993) describe an optically based system for detecting the presence of ice on aircraft wings during ground inspection based on the reflectivity of ice at differing wavelengths.”

*“Similarly, Gregoris et al. (2004) describe a system that utilizes **spectral contrast associated with differing reflectivity of ice with varying wavelength to detect and measure ice thickness**. We speculate that the method could suffer from inaccuracy in thickness measurement when the surface is at substantial angles to the sensor line of sight and when the ice has air bubble inclusions.”*

In case of a measurement system mounted on the nacelle, the angle between the line of sight and the blade surface is very unfavourable. Therefore the method proposed by Gregoris should be first validated in these conditions. An alternative solution could be to mount the instrument on a met-mast. This solution does not come without drawbacks. In fact to obtain a good angle of sight on all the blades of a rotor, the distance between the sensor and the turbine need to be large enough, reducing the spatial resolution and the accuracy. That would require further investigations to consider this method mature for ice-detection on blades of operating wind turbines.

Blackwood (1993) uses the bi-refrigent properties of ice for detection where polarized light is directed at a surface with a layer and the returning light, after passing through the layer, is analysed for altered polarization that would indicate the presence of a bi-refrigent material, e.g. ice. A method that utilizes laser interferometry to measure ice thickness has been described by Gagnon (1997). Interference fringes are counted as the optical path of a laser beam through an ice layer is altered in a controlled manner by changing the angle of incidence or alternately by changing the wavelength of the laser in a continuous manner while the geometry remains fixed. The method would be limited to transparent materials with no air bubble inclusions, such as glaze ice.

This method suffers the same major drawback of being blind to glaze-ice.

A remote non-contact icing thickness sensing device capable of accurate measurements at considerable distances (>20 m) is described in the paper of Gagnon. *“The device, known as RIDE (Remote Ice Detection Equipment), incorporates two optical methods to detect and measure ice and fluid layers. One method is for relatively clear layers, such as glaze ice and water layers, and the other technique is suited to foggy ice, such as rime ice, and translucent liquid layers.”* [29]

This seems promising but further investigations must be carried out to verify reliability on field.

3.10 Commercial products for icing detection

- **Moog Insensys Fibre Optic Rotor Monitoring System (RMS).** The system uses two methods: monitoring of the root bending moment in the time domain, for detecting ice when the blade is rotating. Analysis of the bending moment frequency spectrum is performed, when the rotor is standstill, to create continuous “ice presence” .
- **Goodrich Ice Detector**
- **Saab Security Systems SSS/Combitech Ice Monitor**
- **IGUS BladeControl**
- **Scaime MDX-8000**
- **Igus Blade Control**

3.11 Conclusion

One of the last benchmarking campaigns carried out in Europe [28] has highlighted the main deficiencies of all ice detection instruments: reliability. In the benchmarking tests two off-the-shelf instruments (SSS/Combitech Ice Monitor and Goodrich Ice Detector) have been tested at different stations subject to different climates. The results are reported in the following extract form [28].

Measurements. During this last winter of the Action, all the operational stations have performed measurements with the two selected icing detectors. A new version of the Saab Security Systems SSS / Combitech Ice Monitor was delivered at the end of the summer 2008. Laboratory measurements showed that the instrument proved a stable behaviour. The sensors were then installed on the test facilities. The results showed quickly that the expected stability increase was not achieved, on the contrary: at all stations, the instability on the field proved to be similar and even worse than before. Dependency on outside temperature, wind speed and direction was analysed, without obvious correlations. SSS recognized the problem and an

updated version could be tested in real conditions first in Sweden: the results proved to be positive and the new sensors were shipped in February/March 2009 to all the COST stations. Preliminary measurements have showed that this time a real improvement had been achieved, but for most of the stations the winter icing periods were more or less already over.

Results of measurements. Goodrich ice detector: the sensor proved to be working correctly and give most of the time information on the beginning of the icing period. Unfortunately, as the ice accretion increases, the instrument gets covered by ice creeping from the mounting of the sensor and – due to the heating – is finally surrounded by a hollow ice sphere preventing any ice detection until the next melting period. Furthermore, in some cases – not clearly understood yet -, the instrument does not react at all. SSS / Combitech IceMonitor: the latest version of the instrument seems to show the required electronic stability. However, due to the late installations in the winter, only very few icing periods could be recorded. Furthermore, the problems of ice accretion on the body of the instrument preventing its free rotation remains unsolved, at least until a new prototype with forced rotation can be tested.

The general conclusion is that at present time, even though some ice-detector systems are available on the market, none of the one tested by independent research groups has shown the reliability needed by such an important component: the sensors will need more development, which could be best achieved only in the framework of international projects.

Ice detectors will have to be further tested and certified, as icing measurements are essential not only for the condition monitoring of wind turbines, but also for the verification of icing models which are widely used to predict formation of ice.

4. Rotor unbalance

Ice formation is a phenomenon that requires specific techniques to be identified, as described in the previous chapter. Ice formation and accretion are in fact related to peculiar atmospheric conditions, which make the ice detection a big challenge.

From a more general perspective ice formation can be considered as one of the possible causes of rotor unbalance. *“There are two main imbalance causes: the so-called mass imbalance arising from inhomogeneous mass distributions caused by, e.g., manufacturing inaccuracies or water inclusions in the blades texture, and aerodynamic imbalances, arising, e.g., from errors in the pitch angles or profile changes of the blades”* [30].

Figure 14 shows a lumped parameters model of a 3 blades rotor. Each blade can be represented by a lumped mass m_i in the blade's centre of gravity, which is identified by its radial position r_i . When the rotor is in operation each blade experiences a radial centrifugal force

$$F_{c_i} = m_i r_i \omega^2$$

The condition of mass balance on the rotor plane can be written as:

$$m_1 r_1 = m_2 r_2 = m_3 r_3$$

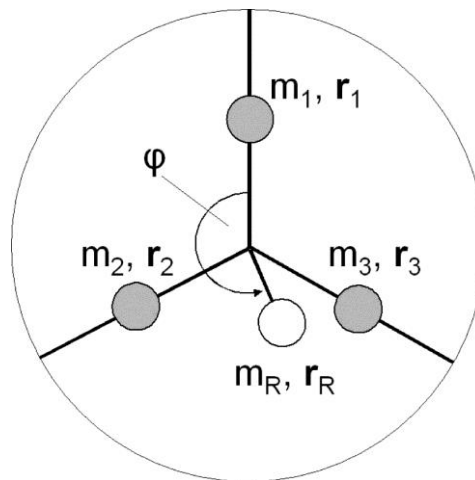


Figure 14: Mass unbalance.

From this we can see that any time one of the parameters $m_i r_i$ ($i=1,2,3$) changes, the rotor is in a state of imbalance.

A rotor mass imbalance can be described as a virtual mass m_R at a virtual distance r_R . This mass induces a resulting centrifugal force perpendicular to the rotor axis. This unbalanced force enters through the shaft into the generator, gearbox, nacelle and tower, to be resisted by a counteracting one by the soil. In the path from the rotor to the soil the unbalanced force produces additional internal actions on the structure.

The unbalanced force leads to a periodic oscillation of nacelle at 1p, perpendicular to the rotor axis. The amplitude of the oscillation is a measure for the magnitude of the mass imbalance (when the damping conditions of the system have been considered). The virtual position of the resulting mass m_R , given by the angle φ in Figure 14, points to the blade responsible for the imbalance.

Due to the construction principles of a horizontal axis wind energy converter the point of attack of the centrifugal forces at the blade root is not in line with the tower axis but has a distance of some meters to it. This results in a small excitation share of a torsion nacelle oscillation but in a degree which can be neglected according to rotor mass imbalance monitoring [30].

Aerodynamic rotor asymmetries are caused by different angles of attack due to assembling faults of the blade pitch drive. Another reason could be a difference in the blade profiles caused by production tolerances or permanent deformation during operation. Even an ideally aerodynamic symmetric rotor induces periodic excitation to the nacelle of the wind energy converter. Due to the wind shear and to the fact that the arm of lever is longer, a blade induces a higher thrust force to the nacelle when it is in upright position (this is another component which acts with the frequency 1p). The tower shadow effect, which occurs when a blade passes nearby the tower, is instead a 3p forcing for the structure (for a 3 blades rotor).

In addition to the faultless operation forces, periodic forces due to aerodynamic asymmetries of the rotor generate two different types of nacelle oscillations at the rotor angular frequency (the 1p-frequency). One type is the above mentioned axial oscillation, the other type is a torsion oscillation around the vertical tower axis. Cause for both oscillation types are the different bending moments imposed to the nacelle, which are generated by the individual blade thrust. Related to the axial oscillation, this bending moment is maximum, when a blade is in the vertical upright position. For the torsion oscillation the maximum bending moment is experienced when a blade is in horizontal position.

Since the aerodynamic forces are very sensitive to the angle of attack (related to pitch angle faults) or to the blade profile (related to profile deformations), aerodynamic asymmetries of the rotor lead to significant differences in the thrust for the individual blades. This happens once per rotor revolution. Therefore, the regular 3p oscillations are superposed by an additional 1p axial and torsion oscillation component of the nacelle.

Monitoring the amplitude of these 1p oscillations provides a measure for the magnitude of aerodynamic rotor asymmetries. The phase angle of the oscillation related to the absolute rotor position points to the blade, which causes the asymmetry.

All the above mentioned effects will be additionally influenced by an incoherent wind field over the rotor swept area. Since these influences are random distributed, monitoring and averaging over a suitable number of time windows with an appropriate length will erase their interferences from the 1p amplitude and phase information.

4.1 Working principles

Rotor unbalance means that either the mass of the rotor or the aerodynamic forces are not homogeneous with respect to the angular position, but azimuth dependent. Therefore, for an

unbalanced rotor, there will be an increased presence of the main frequency and its multiples in the Fourier spectrum of a signal recorded on the main shaft or nacelle. This is the way unbalance can be found on an operating turbine.

Two kinds of rotor unbalance detection strategies can be adopted:

- **Detection of strain level on the root laminates of each blade** (as already seen in some ice-detection systems)
- **Detection of accelerations on the nacelle** of the turbine.

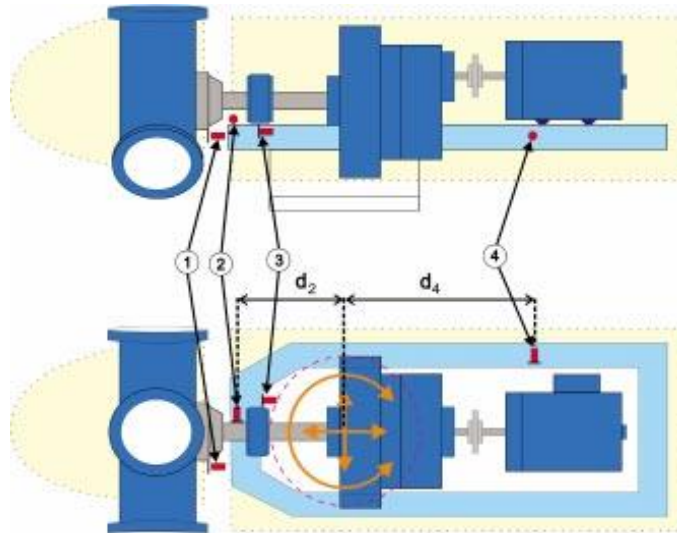


Figure 15: Accelerometer in the nacelle for rotor unbalance monitoring.

4.2 Practical configuration

The first strategy (strain level detection on the single blades) requires 3 or 4 rosette strain gauges mounted on the inner surface of the root laminates of each blade. Bragg gratings are preferable for their proven stability on a long time span, with respect to copper foil counterpart. A conventional configuration consists of 4 strain gauges mounted on 2 perpendicular axes on a transverse section of the blade. This configuration allows retrieving 2 bending moments about the two axes and the axial forces acting on the blade.

The signals have to be processed and through a learning process it is possible to assess the level of unbalance in the rotor. The main drawback of this strategy resides in the fact that strain sensors in blades are subject to a harsh environment and, in case copper ones are used, they are sensitive to damage if the blade is hit by lightning. The main advantage is that each blade can be monitored and that gives a better insight in the issue of each blade.

For applying the second strategy, a number of accelerometers are needed in the nacelle. Figure 15 shows a typical sensor configuration for measuring the nacelle oscillation of a horizontal axis wind energy converter. Since rotor imposed nacelle oscillation frequencies are very low (typically from 0.1 Hz to 10 Hz), accelerometers with a bandwidth [0-500 Hz] need to be used.

There are three oscillation modes of the nacelle, which are relevant for rotor condition monitoring and fault prediction: transverse to rotor axis, in line with rotor axis and torsion around vertical tower axis. These oscillation modes are shown in Figure 15 (see orange arrows). To monitor these oscillations, three acceleration sensors are required.

The sensor with label 3 in Figure 15 is sensitive in axial direction (related to the rotor axis). Sensors at labels 2 and 4 are sensitive in transverse direction to the rotor axis. The sensor shown at label 1 is an inductive distance sensor. This sensor gives a reference signal for the absolute rotor position, when one blade is in vertical upright position. This blade by definition is blade 1. Rotor position information is required to calculate the phase information, which helps detecting the rotor faults mass imbalance and aero- dynamic asymmetry.

The acceleration sensors provide a voltage output signal, which is connected to the respective analogue input channels of the CMS. Acquisition rate for the acceleration signals is 100 Hz. Low pass filtering of the data is done with a cut-off frequency of 40 Hz before ADC. The digital values then contain information of all relevant nacelle oscillation frequencies to perform the monitoring tasks.

4.3 Commercial systems

Unbalance systems based on monitoring each blade bending moments are:

- **Scaime MDX-8000**
- **Igus Blade control**

Regarding the second strategy, namely monitoring the nacelle acceleration, any off-the-shelf accelerometer and inductive distance sensor can be used with the appropriate bandwidth and with in-house software.

5. Lightning detection systems

5.1 Introduction

Lightning discharge events are random in nature. With the increasing height and rated power of the wind turbines, the potential number of lightning strikes rises to the square of the height, as well as the average lightning current peak value [31]. This latter registered on high structures like wind turbines, can vary from few kA up to 200 kA, with a featured mean value of approximately 30 kA [32].

Statistically, most of the lightning strikes to a wind turbine hit the blades, since they are the most exposed part of the turbine. From the attachment point to the ground, the current flows through the lowest impedance paths available; this usually passes through the hub and parts of the nacelle to the tower. On its way the current can severely damage electrical and mechanical components [33]. Therefore, lightning damages to wind turbines can be severe, and their impact on the costs can be high in terms of repairing or replacement of the equipment. According to [34], they are at the moment the single largest cause of unplanned downtime for wind turbines. Lightning protection systems for wind turbine rotor blades are a fundamental feature that can avoid the creation of structural damages, which creates a dangerous impact on the maintenance cost and on the health and safety of the machine. To assess and improve this protection, it is necessary to equip the wind turbines with specific lightning detection systems, able to measure, monitor and optimize lightning discharge and flow phenomena. Working principles of the lightning protection and detection systems are reported in the next paragraph.



Figure 16: Lightning strikes on wind turbine (Kansas, USA) [35].

5.2 Working principles

A brief description of the lightning protection systems and a more detailed explanation of the detection system are reported in the following section. More attention is given to detection methods since the actual report is focused on the description of monitoring systems for wind turbine blades. Lightning protection system are in fact technologies used to prevent lightning

strikes damages and not to monitor them. Despite that, for a better understanding of the operating principles behind the detection procedures, protection systems are briefly introduced. Most of the information used to compose this section of the report can be found in detail in IEC 61400-24 standard [36].

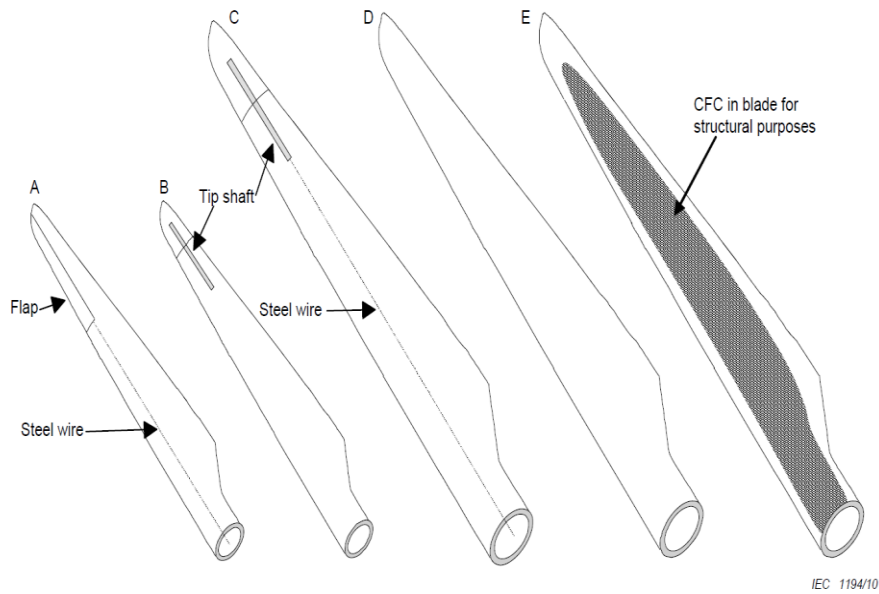


Figure 17: Types of Wind Turbine Blades [36].

5.2.1 Types of wind turbine blades

According to the material layup and the presence of special components such as the tip shaft for blades with the tip brakes, wind turbine blades can be divided in categories. It is important to describe these types, because differences in blade characteristics can change the location of lightnings attachments, influencing the selection of lightning protection systems and consequently detection systems. It is important to remark that lightning does strike blade without any metallic components; this can be partly explained by the fact that pollution, saline pollution, water or humidity make these components more conductive over time. Wind turbine blade types are shown in Figure 17, while a brief description is reported in Table 2.

Typical types of damage at the lightning attachment points are delamination and incineration of the surface composite material, and heating or melting of metallic components serving as attachment point. Severe damages can occur when lightning forms high energy arcs inside the blade between surface skin layer and the air volume inside the blade or the air volume in the internal surfaces and in glue cracks. The pressure shock wave caused by such internal arcs may literally explode the blade [30].

| TYPE | DESCRIPTION | LIGHTNING ATTACHMENT POINTS | DAMAGE |
|----------|---|---|--|
| A | Flap on the outer part of the leading edge for braking | Steel flap hinges and steel wires for flap control | Severe – steel wire is usually too small to conduct properly the lightning current |
| B | Tip brake that is activated by centrifugal forces of excessive rotational speed | Few tens centimetres from the outermost tip of the blade or on the sides of the tip at the position of the outermost end of the tip shaft | Severe – no conduction path for the arcs |
| C | Tip brake controlled by a steel wire | Few tens centimetres from the outermost tip of the blade or on the sides of the tip at the position of the outermost end of the tip shaft | Low – steel wire is able to conduct the lightning currents |
| D | Entirely made of non-conducting materials | Observations show attachments points mostly located close to the tip; they can be also randomly distributed on the length | Not defined |
| E | Some of the structural components made of carbon fibre composite (CFC) | CFC can be integrated in the protection system due to its electrical properties which allows a good conduction of the electrical current | Not defined |

Table 2: Description, lightning attachment points and damages for each wind turbine blade type.

5.2.2 Lightning protection systems

The general method behind all the lightning protection systems available on the market is, according to [30]:

“...to conduct the lightning current safely from the attachment point to the hub, in such a way that the formation of a lightning arc inside the blade is avoided. This can be achieved by diverting the lightning current from the attachment point along the surface to the blade root, using metallic conductors either fixed to the blade surface or inside the blade. Another method is to add conducting material to the blade surface material itself, thus making the blade sufficiently conducting to carry the lightning current safely to the blade root. Variations of both these methods are used with wind turbine blades.”

Examples of lightning protection concepts for large modern wind turbine blades are shown in Figure 18, while a brief description regarding the functioning of the different lightning protection systems is reported in [36].

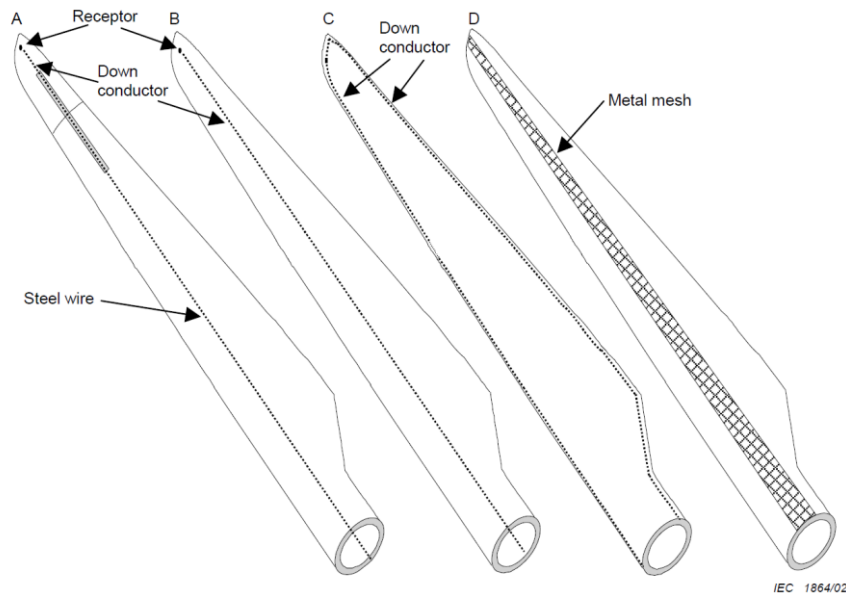


Figure 18: Examples of lightning protection concepts for large modern wind turbine blades [36].

| TYPE | DESCRIPTION | SIDE EFFECTS |
|---|---|---|
| Lightning air-termination systems on the blade surface or embedded in the surface | Metallic conductors installed on the surface; wires or braids of either aluminium or copper embedded in the surface | May compromise the aerodynamics or generate undesirable noise |
| Adhesive metallic tapes and segmented diverter strips | Adhesive aluminium tape placed on the blade surface | Tendency to peel off; substitution may be needed after one strike |
| Internal down conductor system | Metallic fixtures that runs through the blade length, penetrating the surface at the tip to place receptors (Type A and B in Figure 18) | None |
| Conducting surface materials | Conducting material such as carbon fiber is added on the outer layers. Alternatively, blades can be made with a metal mesh placed under the gel coat (Type D in Figure 18), or the extreme tip can be made of metal or covered with a metal sheet | None |

Table 3: Lightning protection systems [36].

5.2.3 Lightning detection systems [36]

In order to monitor and to optimize the performances of the lightning protection procedures applied, wind turbines are equipped with equipment to detect lightning strikes and to monitor the current levels of these phenomena. The purposes of such systems are:

- Provide information to the operator on the level of lightning strikes that have affected the wind turbine and to play a part in operation and maintenance regimes.

- Provide valuable data on the expected number of lightning strikes to tall wind turbines and to assess their magnitude and characteristics, aiding in future risk assessment processes.

The existing options for detection systems are described below.

Wide area lightning detection systems

These systems are made of antennae able to detect electromagnetic impulses produced by the lightning flash. They use multiple antennae to locate lightning flashes based on direction finding or time of the arrival techniques. Data from these systems are generally available in real time. The data output will not normally allow the exact lightning flash to be pinpointed as the accuracy of such systems can be limited from a few hundred meters to a few kilometres (the accuracy depends on the relative location of the lightning flash to the antennae and its magnitude).

Local active lightning detection systems

Sensors are mounted on the tower of the wind turbine to trigger a lightning alarm based on magnetic field criteria. Antennae can prevent remote lightning flashes from triggering false alarm. Such systems can be connected to a SCADA system giving a useful indication of lightning strikes real time. Obviously, the system is not able to detect the location of the strike, but it can give data on waveform and magnitude of the lightning. It is possible to integrate the transducers (Rogowski coil or the use of a fibre optic based technique) directly in the blade protection systems.

Local passive lightning detection systems

Peak current sensor (PCS) cards have a magnetic strip with a pre-defined field pattern. They are clamped to a down-conductor, and the pre-defined pattern is partially erased by the magnetic field of the current flowing through the wire. The higher the lightning current, the higher the magnetic field around the down conductor and the more of the pre-defined field pattern is erased or distorted. This form of system typically claims to have a detection range of 3 kA to 120 kA with results deviating not more than ± 2 kA. The cards only record peak currents and have the capability of storing only one such reading. Thus, in the event of multiple lightning strokes, only the highest peak current among all the strokes is stored. There is no time reference and they cannot be interfaced into a SCADA system or similar.

5.3 Survey of available equipment

In the following section, a survey of the available equipment for the different existing options for detection systems is reported. The survey contains also a list of the function capabilities of the technologies reported along with descriptions of the accuracy, the practical configuration, collection data software and hardware platform requirements.

There are several companies on the market providing products and services related to lightning protection and detection systems, offering a wide and different set of possible applications for their commercial products. Some of the technologies developed, even though they are specifically thought for wind energy applications, can be eventually installed on turbines. Despite that, in the next pages only companies providing and having experience with systems applied to wind turbines have been reported, since it can be assumed that they can offer higher quality products and service for wind energy applications.

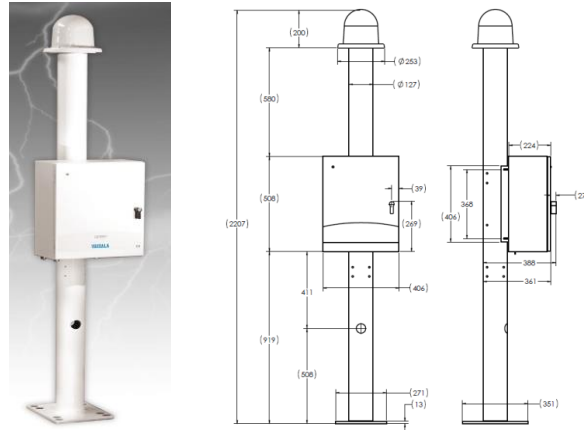


Figure 19: Vaisala Thunderstorm CG Enhanced Lightning Sensor LS7001 layout [38].

5.3.1 Wide area lightning detection systems technologies

One of the most important companies in the field of thunderstorm and lightning detection system products is the Finnish Vaisala [37]. It offers different solutions that vary in terms of detection accuracy range.

Vaisala Thunderstorm CG Enhanced Lightning Sensor LS7001 [38]

This system is used for cloud-to-ground lightning sensing using a detection technology based on magnetic field low frequency signals combined with time-of-arrival technology. The sensor is capable of detecting a lightning at long ranges (>1500 km), recording time, location, amplitude and polarity. It has 250-500 m median location accuracy for lightning strokes. Another capability is the possibility to install the sensor separately from the antenna in remote severe weather locations.

Regarding practical configuration and hardware platform:

Operational Specifications

| | |
|----------------------------------|--|
| Lightning Type | Cloud-to-ground (CG) flashes and strokes and cloud flashes |
| Network Detection Efficiency | >90% for CG; 10-30% for cloud |
| Network Median Location Accuracy | 250-500m CG stroke |
| Nominal Baseline Between Sensors | 15 to 350 km |
| LF Band | 1kHz-350kHz |
| Performance Monitoring | Complete manual and automatic system calibration and self-test |
| Remote Configuration | Operational parameters are remotely configurable |

Synchronization

| | |
|----------|------------------------|
| Source | GPS receiver |
| Accuracy | 100 nanoseconds to UTC |

Mounting

| |
|-----------------------------------|
| 2m Ground mount with concrete pad |
| Roof mount option available |

| Dimensions | |
|------------|------------|
| Weight | 37.4 kg |
| Height | 2.2 meters |
| Width | 0.4 m |
| Depth | 0.4 m |

| Power Requirements | |
|--------------------|------------------------------------|
| AC Power | 100-250VAC, 2.4-1.2A max, 50-60 Hz |
| DC Power | 48VDC (36-72 VDC), 2.7-1.4A max |

| Operational Reliability | |
|-----------------------------------|---------------|
| Mean time between failures (MTBF) | >30,000 hours |
| Mean time to repair (MTTR) | <1 hours |

| Environmental Conditions | |
|--------------------------|------------------------------|
| Temperature | -40°C to +55°C |
| Relative Humidity | 0 to 100% condensing |
| Wind Speed | 0-240 km/h |
| Altitude | Up to 5500 meters |
| Hail | 2.0 cm in diameter |
| Ice | 8 cm |
| Rain | 8 cm/h at wind speed 65 km/h |

Vaisala Thunderstorm Total Lightning Sensor TLS200 [39]

This sensor uses a similar technology of the one reported above with the difference that this detection technology is based on magnetic field low frequency and very high frequency signals (again combined with time-of-arrival technology). The system is capable of detecting a lightning at medium ranges (1-2 km). It has 250 m median location accuracy for lightning strokes. It includes also the capability of remote configuration and 4 hours of uninterrupted power supply in case of loss of power to site. In the following tables, practical configuration and hardware platform is reported.

| Synchronization | |
|-----------------------------------|--|
| Source GPS receiver | |
| Accuracy +/-50 nanoseconds to UTC | |

| Operational Reliability | |
|-----------------------------------|---------------|
| Mean time between failures (MTBF) | >30,000 hours |
| Mean time to repair (MTTR) | <30 minutes |

| Mounting | |
|---|--|
| 10 m ground mount with concrete pads for mast | |
| 5 m roof mount option | |
| 2 m tower mount option | |

Environmental Conditions

| | |
|-------------------|------------------------------|
| Temperature | -40 °C to +50 °C |
| Relative humidity | 0 to 100 % condensing |
| Wind speed | 0-260 km/h |
| Altitude | up to 5500 meters |
| Hail | 5.0 cm in diameter |
| Ice | 1.0 cm |
| Rain | 8 cm/h at wind speed 65 km/h |

Communication Interfaces

Asynchronous RS-232 at 38,400 bps minimum (data only)

Ethernet (recommended for full functionality)

Power Requirements

100-120 VAC, 6.0 A max., 50-60 Hz

200-240 VAC, 3.6 A max., 50-60 Hz

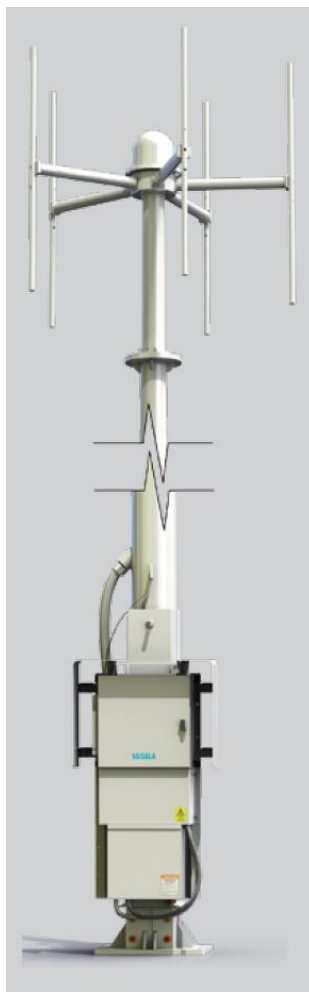


Figure 20: Vaisala Thunderstorm Total Lightning Sensor TLS200 scheme [39].

To conclude the section regarding this type of sensors, a brief description of the collection data software required is reported. The processor compatible with the selection of sensors offered by Vaisala is called the Vaisala Total Lightning Processor series TLP100 and TLP 200 [40]. Technical data are reported below.

Fully Supported Sensors

| | |
|----------------|----------------|
| TLP100™ Series | LS7000, LS7001 |
| TLP200™ Series | LS8000, TLS200 |

Capacity Up to 512 Sensors

Up to 512 for LF only, 256 for LF + VHF data

Supported Communication Interface

TCP/IP

Asynchronous RS-232 (optional)

Supported Web Browser Interface

Mozilla Firefox 3.0 (recommended), 2.0 (supported)

Internet Explorer 7

Certified Hardware

DELL™ POWEREDGE™ T310, Desktop Server

DELL™ POWEREDGE™ R310, Rack Mount Server

Certified Hardware Requirements

4GB of RAM

Dual Core x86_64 compatible CPU

2 (1)TB SATA II disk, RAID 1

2 x NIC ports (100/1000 Mbps)

4 USB 2.0 ports

1280x1024 certified video adapter and monitor

DVD+-RW Burner

Graphics card with hardware accelerated drivers compatible with RHEL 5.3 (512MB RAM, PCI Express Interface). ATI Radeon HD 4350 GPU (recommended)

Red Hat Enterprise Linux® (RHEL) 5.5, 64 bit edition

RHEL 5.5 compatible modem

Environmental Specifications

The hardware must be in a climate-controlled environment. The environmental specifications are equal to the HW specifications by default. The following specifications are subject to change without notice based on hardware availability.

| | |
|-----------------------------|--|
| Operating Temperature | 10 °C to 35 °C |
| Storage Temperature | -40 °C to 65 °C |
| Operating Relative Humidity | 20 % to 80 % non-condensing (non-condensing twmax=29 °C) |
| Storage Relative Humidity | 5 % to 95 % non-condensing (twmax=38 °C) |
| Operating Altitude | -16 to 3,048 m |
| Storage Altitude | -16 m to 10,600 m |

Lightning Detection parameters

| |
|--|
| CLOUD DISCHARGES and CLOUD-TO-GROUND STROKES |
| Date and Time to 100 nanosecond resolution |
| Latitude and Altitude |
| Number of sensors used in location solution |
| Position confidence ellipse (chi-square) |
| Degrees of freedom when optimizing the solution |
| Semi-major axis of the 50 % positional confidence ellipse (km) |
| Semi-minor axis of the 50 % positional confidence ellipse (km) |
| Eccentricity of the positional confidence ellipse |
| Estimated Rise Time (microseconds) |
| Estimated Peak-to-Zero Time (microseconds) |
| Estimated Maximum Rate-of-Rise (kA/microsecond) |
| CLOUD TO GROUND STROKES (only) |
| Flash multiplicity (number of return strokes) |
| Polarity |
| Estimated Peak Current (kA) |

5.3.2 Local active lightning detection systems technologies

Vaisala offers also a product for local active lightning detection. This system is briefly described below.

Vaisala Thunderstorm Total Lightning Sensor TSS928 [41]

The sensor uses optical, magnetic and electrostatic pulses from lightning events to provide an alarm in case of strike in a range of 56 km. The lightning can be classified within three range intervals (0-9, 9-19, 19-56 km) in different directions (N, NE, E, SE, S, SW, W, NW). Technical data about this technology are reported in the following tables.

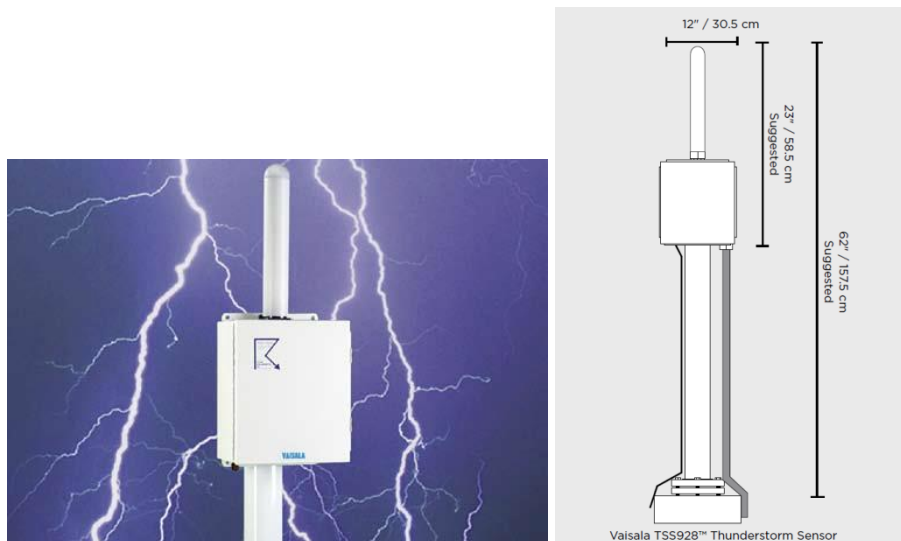


Figure 21: Local Lightning Sensor TSS928TM Layout [41].

Detection Range

56 km radius from sensor location

Bearing Resolution

1° increments, 0° to 360°, reported by octant

Range Resolution

0-5 nautical miles (0-9 km), 5-10 nautical miles (9-19km) and 10-30 nautical miles (19-56km) (range can be set in nautical miles or kilometers).

Thunderstorm Detection Efficiency

90% within 10 nautical miles with one discharge; 99% with two discharges; 99.9% with three discharges

Electrical Specifications

| | |
|----------------------|--------------------------|
| AC Power | 115VAC±10% to 230VAC±10% |
| DC/AC Power | 11-32VDC, 115VAC±10% |
| DC Power | 11-32VDC |
| Power Consumption | 100 watts maximum |
| Standards/Approvals: | UL, CSA, CE |

Communications

Metallic or fiber optic links

Serial ASCII format

RS-232 and RS-422 serial at 9600 bps

Output via automatic one-minute preset weather messages, instantaneous broadcast of data as event occurs or sensor can store and be polled by user.

Mounting Configuration

Ground mount option

Roof mount option with tripod

Frame mount for either roof or ground options

| | |
|--------|------------------------------|
| Height | 3.0 m max height recommended |
|--------|------------------------------|

Environmental Conditions

| | |
|---------------------|------------------------------------|
| Operating/Storage | |
| Temperature Range | -50°C to +50°C (with heater) |
| Maximum Wind Load | 0–120 knots, 222 km/h |
| Humidity Tolerance | 0% to 100% |
| Siting Requirements | Flexible installation requirements |

ALARM (Automated Lightning Alert and Risk Management) system software is used to visualize the data output of this sensor [42].

Data collection software requirements are described in the tables below.

Operating System

Microsoft Windows XP (SP 3.0), Windows 7 (SP 1.0)

Hardware Requirements

| | |
|-------------------|---|
| Personal Computer | Desktop |
| Processor | Pentium® III 750 MHz (minimum 500 MHz) |
| RAM | 256 MB |
| Hard Drive Space | 20 GB |
| Ports | 2 serial |
| Monitor | 17" (choose from standard and flat screen options) |
| Resolution | 1024 x 768 pixels (or higher) |
| Color Depth | 24 bit |
| Peripherals | CD-ROM drive, floppy drive, surge suppressing power strip |

Communications

The standard data link between the Vaisala ALARM system and Vaisala electric field mills and Vaisala local lightning is by direct serial connection via two RS-232 ports.

Communications Options

Communications card (32-bit PCI, 8 serial ports)

For connecting to sensors within 10,000 feet of the system, communications hardware is a RS-232 cable, a RS-232/RS-422 interface, and a RS-422 cable.

Other configurations are available for distances exceeding 10,000 feet.

Additional Options

| | |
|------------|--|
| Relay card | 32-bit PCI, eight outputs; termination card and connecting cable |
| UPS | APC 1000 VA, 120V or 240V Battery pack for UPS extended backup |

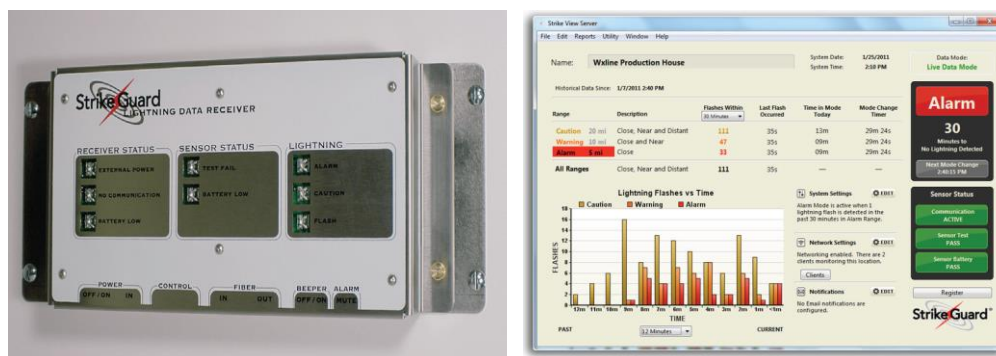


Figure 22: WXLINe's Strike Guard Lightning Warning System [44].

Another company that offers commercial solutions for lightning detection applicable to wind turbines is the American WXLINe with its brand Strike Guard Lightning Warning System [43].

Strike Guard Sensor [44]

The system provides audible and visible alarm in case of lightning strike. It monitors cloud and cloud-to ground lightning within a user-set range and provides contact-closure sending signals

at user-set lightning activity thresholds. Strike Guard Sensor data are communicated via lightning-proof fibre-optic cable to an independent Lightning Data Receiver with system status, caution and alarm indicators, relays, and computer compatible output. Strike Guard enables automated initiation of lightning evacuation plans, data back-up, generator activation, and equipment shutdown procedures.

Lightning Data Receiver Specifications

| | |
|--------------------------------|---|
| Installation | Wall-mountable with size 10 screws |
| Enclosure | Type 304 stainless steel |
| Battery | User-replaceable alkaline C-cells. Low battery indicator |
| Communication | Connector-less fiber-optic link for Sensor input and output to computer Integral Sensor data repeater |
| External Control | 2 relays, single pole, double throw. 1 A at 120 VAC, UL, CSA approved |
| Lightning Alarm Range Settings | <5 miles, <10 miles or <20 miles |
| Settings | Lightning alarm range, alarm timeout, and lightning counts for contact-closure signaling |
| Audible Notification | Alarm Mode, Lightning Flash |
| External Power | In-line switching power supply. Input 100-240 VAC, 50/60 Hz. UL, VDE, FCC, CSA, CE |

Sensor Specifications

| | |
|-------------------|--|
| Installation | Materials and hardware included for roof-mount |
| Site Requirements | Minimal siting restrictions |
| Enclosure | NEMA 4X |
| Communication | PMMA fiber-optic, 100 ft cable included |
| Battery | Lithium primary cells, 4-year life minimum |

WXLINE provides a collection data software compatible with the Strike Guard Sensor [45]. The technical data for this software, which is called Strike View, are reported in the next table.

Strike View Software Specifications

| | |
|-----------------------|---|
| Computer Requirements | 256MB; Pentium III or higher recommended |
| Platform | Microsoft Windows® 2000/XP/Vista/Windows® 7 OR Macintosh OSX |
| Interface | Strike Guard RS-232 to Fiber-optic Converter to PC's 9-pin serial or USB port |
| Format | Installation CD or thumb drive |

5.3.3 Local passive lightning detection systems technologies

The Danish company Global Lightning Protection Services based in Herning, Denmark produces a system based on the local passive lightning detection method. A brief description of this system is reported below. The company offers also services in terms of lightning protection and detection systems testing and education [46].

GLPS Lightning Registration System [47]

The lightning registration system consists of three components and the sensor card can be mounted on both land and offshore wind turbines that are already operating. The three components are:

1. Lightning sensor card installed in a card holder
2. Card reader
3. Analysis and reporting software

When a lightning strike is led to ground via a lightning down conductor, a magnet field is created around the conductor. The strength of the magnet field is proportional with the amplitude of the lightning current and decreases with the distance to the conductor. By applying a card with a special magnet code vertically on the conductor, the magnet field generated by the lightning current will delete the data in the area where its strength is higher than what the magnetic code can withstand. By assessing the distance from the conductor at which the code is erased, the peak amplitude of the lightning current can be defined [47].

General Specifications

| | |
|----------------------|--|
| Temperature | From -30°C to 80°C |
| Sensor Dynamic Range | 6-300 kA |
| Calibration | The card reader is calibrated in a high-current laboratory, where also correction factors of new specific conductor geometries differing from a circular conductor can be determined |
| Feature | Lightning cards are numbered with a printed serial number. The same serial number is saved in the magnetic code on the lightning card and appears on the analysis report |

Mounting

| | |
|--------------|---|
| Installation | The card holder is fixed to the wind turbine ground holder and the card is installed in the card holder |
| Options | Several cards can be installed in one wind turbine in order to give more detailed information about the lightning attachment point and impact |

Software Specifications

| | |
|------------|--|
| OS | MS Access Database based |
| Connection | The data reader is connected to a personal computer via USB port |
| Feature | When reading the lightning cards it is possible to add a correction factor to compensate for noncircular conductor geometries. |

References

- [1] Hameed Z, Hong Y S, Cho Y M, Ahn S H and Song C K, "Condition monitoring and fault detection of wind turbines and related algorithms: a review," *Renew. Sustain. Energy Rev.*, no. doi:10.1016/j.rser.2007.05.008, 2007.
- [2] Sørensen B F, Jørgensen E, Debel C P, Jensen F M, Jensen H M, Jacobsen T K and Halling K M, "Improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase I)," Summary Report (Risø-Report), Risø National Laboratory, Denmark, 2004.
- [3] Sundaresan M J, Schulz M J and Ghoshal A, "Structural health monitoring static test of a wind turbine blade," Subcontract Report NREL/SR-500-28719, National Renewable Energy Laboratory, CO, USA, 2002.
- [4] Sørensen B F et al, "Fundamentals for remote structural health monitoring of wind turbine blades—a preproject," Risø-R-1336(EN) Report, Risø National Laboratory, Denmark, 2002.
- [5] Ciang C C, Lee J-R and Bang H J, "Structural health monitoring for a wind turbine system: a review of damage detection method," *Mesasurement Science and Technology*, vol. 19, no. i22001, 2008.
- [6] Rao B K N, Handbook of Condition Monitoring, UK: Elsevier, 1996.
- [7] Kessler S S, Spearing S M, Atalla M J, Cesnik C E S and Soutis C, "Damage detection in composite materials," *Composites*, vol. 33, no. B, p. 87–95, 2002.
- [8] Park G, Taylor G T, Farinholt K M, Farrar C R, "SHM of Wind Turbine Blades using Piezoelectric Active-Sensors," in *5th European Workshop on Structural Health Monitoring*, Sorrento, Italy, 2009.
- [9] Zhang H, Schulz M J, Ferguson F and Pai P F, "Structural health monitoring using transmittance functions," *Mechanical Systems Signal Processing*, vol. 13, 1999.
- [10] Farrar C R and Doebling S W, "An overview of modal-based damage identification methods," in *DAMAS 97*, Sheffield, UK, 1997.
- [11] Doebling S W, Farrar C R and Prime M B, "A summary review of vibration-based damage identification methods," *The Shock and Vibration Digest*, vol. 30, p. 91–105, 1998.
- [12] Gross E, Simmermacher T, Rumsey M and Zadoks R I, "Application of damage detection techniques using wind turbine modal data," in *American Society of Mechanical Engineers Wind Energy Symp.*, Reno, NV, USA, 1999.

- [13] Farinholt K M, Taylor S G, Park G, Ammerman C M, "Full-scale fatigue tests of CX-100 wind turbine blades. Part I - testing," *Industrial and Commercial Applications of Smart Structures Technologies*, vol. 8343, 2012.
- [14] Taylor S G, Jeong H, Jang J K, Park G, Farinholt K M, "Full-scale fatigue tests of CX-100 wind turbine blades. Part II - Analysis," *Industrial and Commercial Applications of Smart Structures Technologies*, vol. 8343, 2012.
- [15] "Brüel & Kjær," Brüel & Kjær , 2013. [Online]. Available: <http://www.bksv.dk/Products/analysis-software/vibration/structural-dynamics/operational-modal-analysis/operational-modal-analysis-7760.aspx>. [Accessed 25 September 2013].
- [16] Brüel & Kjær , Transducers and Conditioning, Brüel & Kjær , 2013.
- [17] Mark Senlidge and Torben R. Licht, Piezoelectric Accelerometers and Vibration Preamplifier - Theory and Application Handboo, Brüel and Kjær, 1987.
- [18] Brüel and Kjær, Pulse Analyzers and Solutions, Brüel and Kjær, 2013.
- [19] Raghavan A, Cesnik C E S, "Review of Guided-wave Structural Health Monitoring," *The Shock and Vibration Digest*, vol. 39, no. 91, 2007.
- [20] Sutherland H, Beattie A, Hansche B, Musial W, Allread J, Johnson J and Summers M, "The application of non-destructive techniques to the testing of a wind turbine," Sandia Report SAND93-1380, Sandia National Laboratories, USA, 1994.
- [21] Joosse P A, Blanch M J, Dutton A G, Kouroussis D A, Philippidis T P and Vionis P S, "Acoustic emission monitoring of small wind turbine blades," in *Proc. 21st ASME Wind Energy Symp. in conjunction with 40th AIAA Aerospace Sciences Meeting*, Reno, USA, 2002.
- [22] Anastassopoulos A A et al, "Structural integrity evaluation of wind turbine blades using pattern recognition analysis on acoustic emission data," in *25th European Conf. on Acoustic Emission Testing EWGAE 2002*, Prague, Czech Republic, 2002.
- [23] Avdelidis N P, Almond D P, Ibarra-Castanedo C, Bendada A, Kenny S and Maldague X, "Structural integrity assessment of materials by thermography," in *Conf. Damage in Composite Materials CDCM 2006*, Stuttgart, Germany, 2006.
- [24] Hahn F , Kensche C W , Paynter R J H, Dutton A G, Kildegaard C and Kosgaard J , "Design, Fatigue Test and NDE of a Sectional Wind Turbine Rotor Blade," *Thermoplastic Composite Material*, vol. 15, pp. 267-277, 2002.
- [25] ISO, ISO 12494: Atmospheric icing of structures. ISO/TC 98/SC 3, 2000-07-20 .

- [26] R. Cattin, Icing of Wind Turbines Vindforsk projects, April 2012.
- [27] 1. Expert group study on recommended practices -13 - wind energy projects in cold climates, 1st edition, 2011.
- [28] R. Cattin, COST Action 727, 2009.
- [29] J. G. W. P. R.E. Gagnon, Remote ice detection equipment — RIDE.
- [30] R. R. a. T. T. N. J. Niebsch, Mass and Aerodynamic Imbalance Estimates of Wind Turbines.
- [31] Petrov N.I. and D'Alessandro F., "Lightning to Earthed Structures: Comparison of Models with Lightning Strike Data," in *Int. Conf. on Lightning Protection*, Rhodes, Greece, 2000.
- [32] Chowdhuri P. et al., "Parameters of Lightning: a review," *IEEE Trans. on Power Delivery*, vol. 20, pp. 346-359, 2005.
- [33] Krämer S.G.M., León P.F., Lewke B. and Hernández Y.M., "Lightning Impact Classification on Wind Turbine Blades using Fiber Optic Measurement System," 2007.
- [34] Glushakow B., "Effective Lightning Protection for Wind Turbine Generators," *IEEE Trans. on Energy Conversion*, vol. 22, pp. 221-222, 2007.
- [35] Wilson N., Myers J., Cummins K., Hutchinson M., and Nag A., "Lightning Attachment to Wind Turbines in Central Kansas: Video Observations, Correlation with the NLDN and in-situ peak current measurements," in *EWEA*, Vienna, Austria, 2013.
- [36] "IEC 61400-24 - Lightning Protection," in *International Standard IEC 61400 - Wind Turbines*, Geneva, Switzerland, IEC, 2010.
- [37] Vaisala, "Vaisala," Copyright © Vaisala 2011-2013. [Online]. Available: <http://www.vaisala.com/en/products/thunderstormandlightningdetectionsystems/Pages/default.aspx>. [Accessed 2 October 2013].
- [38] *Vaisala Thunderstorm CG Enhanced Lightning Sensor LS7001*, Vaisala, 2009.
- [39] *Vaisala Thunderstorm Total Lightning Sensor TLS200*, Vaisala, 2012.
- [40] *Vaisala Total Lightning Processor™, TLP100™ and TLP200™ Series on Linux®*, Vaisala, 2012.
- [41] *Vaisala Thunderstorm Local Lightning Sensor TSS928TM*, Vaisala, 2009.
- [42] *Vaisala ALARM Automated Lightning Alert and Risk Management System*, Vaisala, 2011.

- [43] "Strike Guard Lightning Warning System," WXLINe, [Online]. Available: http://www.wxline.com/lightning_warning.php. [Accessed 3 October 2013].
- [44] *Strike Guard Lightning Warning System*, North Calle Castilla, Tucson, AZ (USA): WXLINe.
- [45] *Strike View Software*, North Calle Casita, Tucson, AZ (USA): WXLINe.
- [46] "Global Lightning Protection Services," Global Lightning Protection Services A/S, [Online]. Available: <http://www.glps.dk/>. [Accessed 4 October 2013].
- [47] *GLPS Lightning Registration System*, Herning, Denmark: Global Lightning Registration System.
- [48] J. G. Peter Caselitz, Rotor Condition Monitoring for Improved Operational Safety of Offshore Wind Energy Converters.

Acknowledgements

This work is supported by a grant of the Sino-Danish Renewable Energy Development (RED) Programme Component 2. The supported RED-project is titled “Wind Turbine Rotor Blade Testing Technology Research and Platform Construction” and is entered by and between the Royal Danish Embassy in Beijing, Baoding Diangu Renewable Energy Testing and Research Co. Ltd. and DTU Wind Energy. Danida file reference number is 104.Kina.1.MFS.4-1-2-5. The support is gratefully acknowledged.

DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

We have more than 240 staff members of which approximately 60 are PhD students. Research is conducted within nine research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.

Technical University of Denmark

Department of Wind Energy

Frederiksborgvej 399

Building 118

4000 Roskilde

Denmark

Phone 46 77 50 85

info@vindenergi.dtu.dk

www.vindenergi.dtu.dk